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Computational Fluid Dynamic (CFD) Study of an Articulating Turbine Blade Cascade

by Richard Blocher, Luis Bravo, Anindya Ghoshal, Muthuvel Murugan, and Michael Walock

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14. ABSTRACT

This technical report presents some preliminary work toward a project that seeks to develop a shape memory alloy actuator for rotor and stator blades in aircraft turbine engines that will increase efficiency and extend flight ranges. A major step toward the project's completion is the development of a model that simulates both the fluid-structure interaction in the engine and the mechanical behavior of the shape memory alloy actuator. A simple computational fluid dynamic (CFD) case with 2 pairs of actuated blades is presented as a proof-of-concept. Immediate future work will involve altering the case setups for CFD simulation to more accurately represent the fluid-structure interaction in a real engine with articulating turbine blades.

15. SUBJECT TERMS

computational fluid dynamic, CFD, fluid structure interaction, shape memory alloy, SMA

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Student Bio

Impact of High Performance Computing (HPC) Internship Program Research Experience

Just before participating in the HPC Internship Program, I completed my bachelor's degree at The Ohio State University (OSU). I began my PhD program in Materials Science at OSU in Fall 2016, just after completing my research experience at the US Army Research Laboratory (ARL). My mentorship at ARL gave me the basic understanding of computational fluid dynamics (a subject I had never encountered before) required to successfully navigate this research project. The research experience gained over the summer, as well as the availability of HPC systems for use in computational work, have significantly facilitated the beginning of my graduate career.

Acknowledgments

This research was sponsored by the US Army Research Laboratory and took place within its Vehicle Technology Directorate. I would like to acknowledge Luis Bravo, Anindya Ghoshal, and Mutheval Murugan for their mentorship throughout the internship experience. I would also like to thank the Department of Defense's High Performance Computing centers for the continued use of the Excalibur supercomputer. Finally, I would not have had this experience without my graduate advisor at The Ohio State University, Peter Anderson.

1. Introduction

Efficiency is among the most important considerations in the design of aircraft turbine engines. Modern internal combustion turbine engines have improved significantly in the past few decades; efforts to increase their efficiency have included design innovations to increase the usable air pressure at combustion, which is limited by compressed stall. Such design improvements include the capability of newer turbine blades to have fluid run through them during use[1]—a feature which many newer engines include. A cutaway view of a typical rotorcraft engine is shown in Fig. 1. Although there have been many innovations, opportunities exist for improvements that are largely unexplored. The present initiative aims to enhance the efficiency of aircraft turbine engines through the articulation of turbine blades during flight. The blade pitch chosen for all rotor and stator blades in existing turbine engines is fixed, even though aircraft are operated through a wide range of conditions. Different flight velocities and altitudes, for example, influence air pressures and temperatures, which change the flow behavior of the air. If it were possible to rotate turbine blades to a new angle-of-attack during flight, these changes in the viscous properties of air could be compensated for so that optimal fluid-flow behavior is maintained.[2]

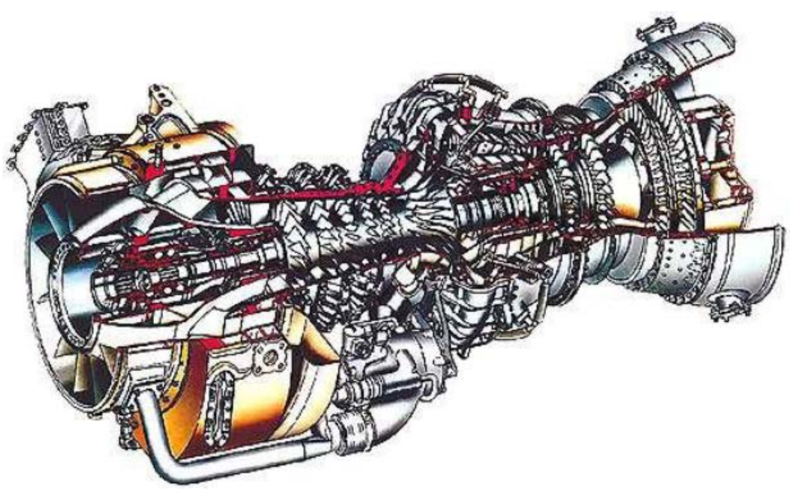

Fig. 1 Cutaway image of typical rotorcraft engine[2]

There are several candidate mechanisms and materials that could be used to achieve turbine blade articulation, but many of these are not plausible. For example, if each blade were individually motorized, the required power and extra weight would negate the benefit of the articulation capability. Piezoelectric materials, which change shape with an applied electric charge, are another option;

however, weight would become a concern because of the relatively low-power density of piezoelectric materials. Shape memory alloys are an option with very high-power density, and they can be operated without the use of motors or hydraulic fluid.

Shape memory alloys (SMAs) compensate for changes in shape through a phase change between austenite and martensite rather than through the creation of dislocations for strains up to around 6%. This phase change can be influenced by either a change in temperature or an applied stress. If a piece of shape memory alloy in the martensite phase is heated to above its transformation temperature, it will undergo a phase change to austenite; the resulting shape change can be used to do mechanical work on the SMAs' surroundings. Figure 2 illustrates the phase composition versus temperature behavior of SMAs.

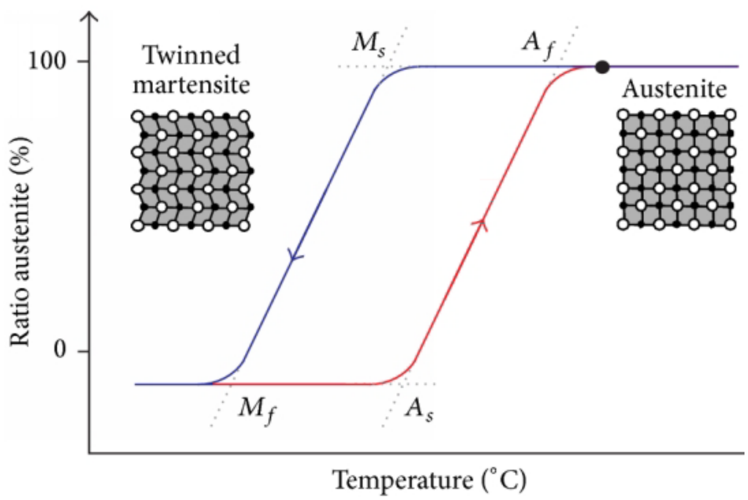

Fig. 2 SMA phase hysteresis[3]

SMAs for the articulation of turbine blades are promising, but there are several challenges associated with them that need to be overcome. For example, the temperature of the air inside the hot section of turbine engines exceeds 1000 °C, while the transformation temperatures of existing SMAs are between 100 and 200 °C.[3] There are various possible solutions to this challenge, such as running coolant across the SMA, housing the SMA itself in a cooler part of the engine, and developing new SMAs with higher phase transition temperatures.

The long-term goal of the project is to develop a working prototype of an actuating turbine blade, but a computational approach will help to answer design questions and concerns without being too costly. Therefore, a computational model of an SMA actuator is an intermediate goal. This model will be developed in the following 3 general steps:

1) Develop a computational fluid dynamic (CFD) model of the fluid-structure interaction between the airflow and the articulating airfoils,

2) Develop a finite-element model of the SMA mechanism, and

3) Interface results from 2 models to achieve a comprehensive model of the actuated turbine blades during engine operation.

Steps 1 and 2 are being worked on concurrently, and the focus of this writing is the first work toward Step 1.

2. Methods, Assumptions, and Procedures

CFD simulations were carried out on a High Performance Computing (HPC) Excalibur, a Cray XC40 System, located at the US Army Research Laboratory's Department of Defense Supercomputing Resource Center.[4] The software chosen for simulation on Excalibur was Converge, which features a fully compressible Navier Stokes equation formulation, fluid-structure interaction modeling for immersed objects, and a parallelized solver with Message-Passing-Interface (MPI) protocols for efficient running on distributed memory architectures (i.e., HPC Excalibur).

Converge also uses a feature called Adaptive Mesh Refinement (AMR) to significantly cut down on computational time. AMR coarsens the cell size in areas where there is little activity. For the simulations carried out in this experiment, the mesh was refined by velocity, meaning the difference in air velocity from one cell to adjacent cells determined how refined the cell size needed to be in that region. See Fig. 3 for an example of what an AMR result for this project looked like.

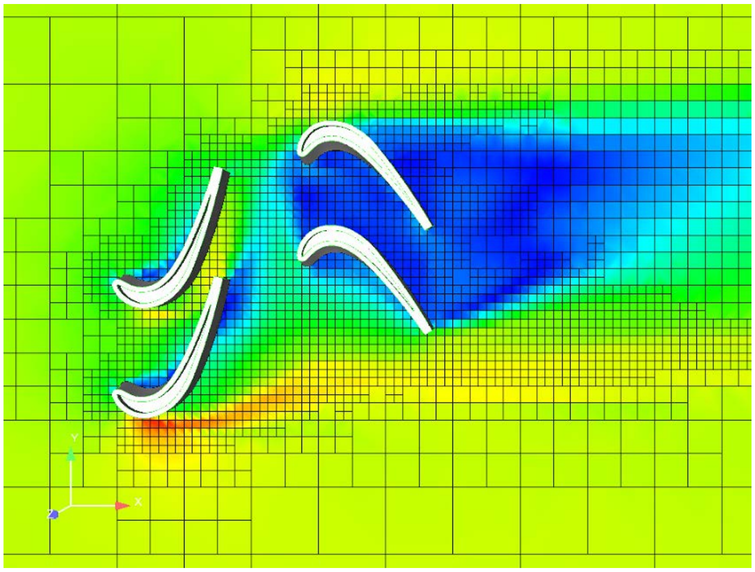

Fig. 3 Refined mesh for 2 rotor-2 stator setup

Figure 4 depicts the case setup used for the results shown in this technical report. The case setup consisted of 2 pairs of blades: 1 pair of rotors and 1 pair of stators. The inflow of air was fixed at 85 m/s, and the walls were defined as inviscid walls. The rotors did not move in the radial direction for this simulation (that motion would be in the up direction in Fig. 4), but the blades were articulated simultaneously in a sinusoidal pattern about the leading edge of the blades with an articulation magnitude of 10°. The AMR parameters for the simulation give a maximum cell size of a cube 2 cm on a side, and the smallest cell size was 1/8 cm in each dimension. The cord length of the blades shown was about 22 mm. The maximum number of cells allowed by the simulation was 2 million; the actual number of cells during the simulation never exceeded approximately 72,000.

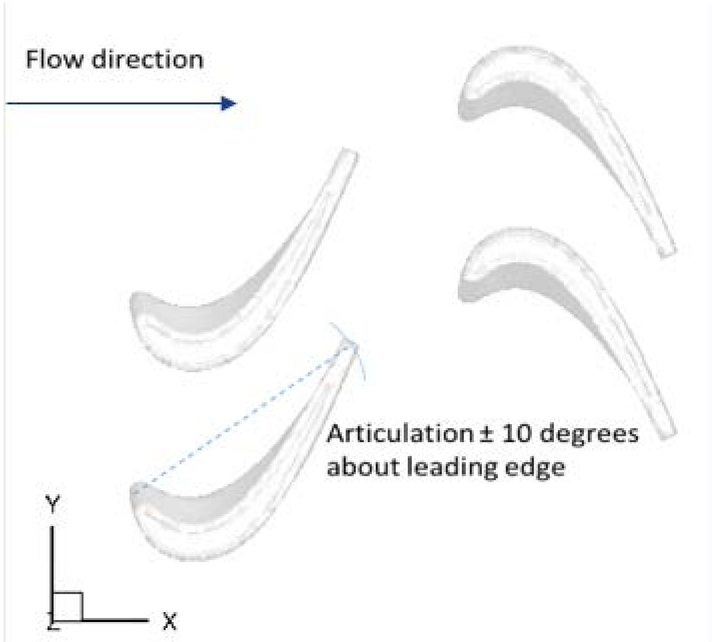

Fig. 4 Case setup for CFD simulation

3. Preliminary Results and Discussion

Figure 5 shows flow velocity fields at 3 extreme points during blade articulation: 10° above normal, no articulation, and 10° below normal. The simulation depicted used an articulation period of 0.5 s; however, simulations were also performed for an articulation period of 0.25 s. Those results were indistinguishable from the ones shown in Fig. 5. Air flow behavior changes depending on the angle of the blades; the flow between the right pair of blades (the rotors) slows when the air is not directed in between them by the stator blades. Of course, in a real engine, there would be an entire ring of blades, so one would expect the boundary layer transitions to be different.

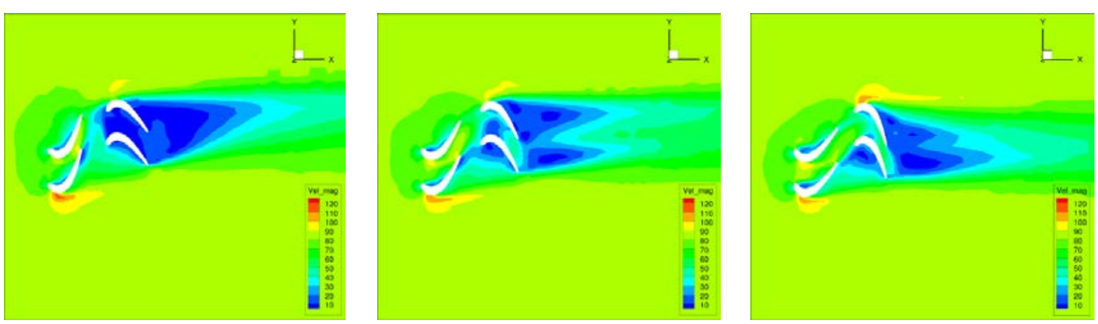

Fig. 5 Velocity fields at 3 points during articulation

4. Conclusions and Future Work

The results gathered thus far serve as a proof-of-concept that the articulation of turbine blades does in fact have a visible effect on the boundary layer behavior in the airflow across the blades. The tools are now in place to develop more rigorous case setups. For example, the number of rotor and stator blades will be increased, with the eventual goal of simulating an entire ring of blades, as in a real turbine engine. The nondimensional governing parameters of the simulation, such as Reynold's number and y+ value, will be rigorously scrutinized to ensure the validity of future results. In addition, various points and patterns of articulation will be studied. The aerodynamic center and center of gravity of the blades, for example, will be tested as points of articulation. The effect of manipulating the phase difference between the 2 sets of blades will also be simulated.

Converge is capable of outputting pressure values at each point on the surfaces immersed in the CFD simulation. Future simulations will fetch these values, which will in turn be used to develop an expression for the moment on some articulating mechanism attached to the blade as a function of angle of attack and rate of change of angle of attack. This expression will be used in a finite-element simulation of the SMA actuator, resulting in a quasi-fully-coupled simulation of the complete actuating mechanism in flight.

5. References

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List of Symbols, Abbreviations, and Acronyms

AMR	Adaptive Mesh Refinement
CFD	computational fluid dynamic
HPC	High Performance Computing
MPI	Message-Passing-Interface
SMA	DOD Supercomputing Resource Center

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
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